INVESTIGATION OF HUMIDITY CONTROL VIA MEMBRANE SEPARATION FOR ADVANCED EXTRAVEHICULAR MOBILITY UNIT (EMU) APPLICATION

Final Report for the Period
April 15, 1988 to February 15, 1989
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PROJECT SUMMARY

Humidity must be controlled in the extravehicular mobility unit (EMU) to prevent visor fogging, to preclude buildup of water than can reduce vent flow and promote corrosion of system components, and for the comfort of the crew member. Techniques currently considered for control of humidity in the EMU include 1) a condenser/heat exchanger with a second-stage rotary water separator, 2) combined humidity/carbon dioxide (CO_2) control using solid-amine technology, 3) combined CO_2/humidity control using a liquid electrolyte, and 4) humidity control using a desiccant bed.(1) However, NASA is considering alternative technologies--including membrane technology--that are less complicated and have lower power requirements.

The objective of this program was to investigate the use of membrane-based technology to control humidity in the EMU. We met this objective by designing, constructing, and testing breadboard hollow-fiber dehumidification modules for this application. During a 90-day test, the performance of these modules remained virtually constant, indicating that long-term, reliable performance is feasible with this technology.

Based on these results, a prototype dehumidification subsystem was designed. This membrane-based subsystem would be very small, have a low mass, and require little power. Consequently, we recommend that a preprototype dehumidification subsystem be constructed and tested under the conditions expected to be present in the EMU. Long-term tests (90 days or more) would be conducted to verify the reliability of this technology.

GLOSSARY OF ABBREVIATIONS

EMU	Extra Vehicular Mobility Unit
BRI	Bend Research, Inc.
NASA	National Aeronautics and Space Administration
JSC	Johnson Space Center
HCCS	Humidity and CO_2 Control System
ERCA	Electrochemical Regenerable CO_2 Absorbent
SEM	Scanning Electron Micrograph

1. INTRODUCTION

This is a final report from Bend Research, Inc. (BRI), to the National Aeronautics and Space Administration's Johnson Space Center (NASA-JSC) for Contract No. NAS 9-17983, entitled "Investigation of Humidity Control Via Membrane Separation for Advanced Extravehicular Mobility Unit (EMU) Application." This report covers the period April 15, 1988 to February 15, 1989.

Humidity must be controlled in the advanced extravehicular mobility unit (EMU) to prevent visor fogging, to preclude buildup of water that can reduce vent flow and promote corrosion of system components, and to provide a comfortable level of cooling for the crew member. Mechanisms used to control humidity in the EMU must be small, have a low mass, and require little power. Additionally, the use of consumables or expendables must be minimized or eliminated. Although regeneration of system components will be performed when the EMU is not in use, regeneration time must be minimized in order to meet contingency requirements.

Techniques currently envisioned for control of relative humidity in the EMU include 1) a condenser/heat exchanger with a second-stage rotary water separator, 2) combined humidity/carbon dioxide (CO_2) control using solid-amine technology, 3) combined CO_2/humidity control using a liquid electrolyte, and 4) humidity control using a desiccant bed.(1) However, NASA is considering alternative technologies--including membrane technology--that are less complicated and have lower power requirements. A membrane-based humidity-control subsystem would use a membrane to selectively remove water vapor from the vent loop. Thus, less air would be cooled in the condenser, and the size of the condenser needed for the membrane-based subsystem could potentially be smaller than the condenser required for conventional systems. Furthermore, there is evidence that biological growth could be more easily controlled--i.e., in this membrane system, no liquid water, which promotes biological growth, ever contacts the EMU atmosphere. This design also promises to reduce or eliminate expendables and, overall, the

the system has the potential to reduce the volume, mass, and power requirements of the humidity-control mechanism.

The goal of this program was to investigate the feasibility of using a membrane-based system to control humidity in the EMU. Specifically, our objectives were 1) to screen dehumidification membranes to identify those that minimize the volume, weight, and power consumption of the membrane-based subsystem; 2) to design and fabricate membrane modules containing these membranes; 3) to evaluate these modules under the range of conditions expected to be encountered during actual use; and 4) to design a preprototype membrane-based humidity-control subsystem for an advanced EMU application.

2. BACKGROUND

2.1. Dehumidification Requirements for the EMU

Figure 2.1.-1 shows a general schematic of the current design of the backpack used in the space shuttle EMU.[2] Air first enters the CO_2-removal subsystem and then passes through the humidity-control subsystem. Make-up oxygen is then mixed in, and the "revitalized" air is sent back to the crew member. Table 2.1.-I lists the design specifications for the EMU.[3]

NASA has investigated several technologies designed to control humidity and CO_2 in the EMU. The current shuttle EMU uses a condenser/heat exchanger and water separator to control humidity and expendable LiOH for CO_2 removal.[4] However, the expendable LiOH beds are unacceptable for an advanced EMU. Thus, NASA has investigated the use of regenerable CO_2-removal systems.[5]

Systems that use regenerable sorbents for removal of CO_2 and water have also been investigated. The humidity and CO_2 control system (HCCS) uses a metal foam and retention screen matrix permeated with a solid amine sorbent.[4,6,7]

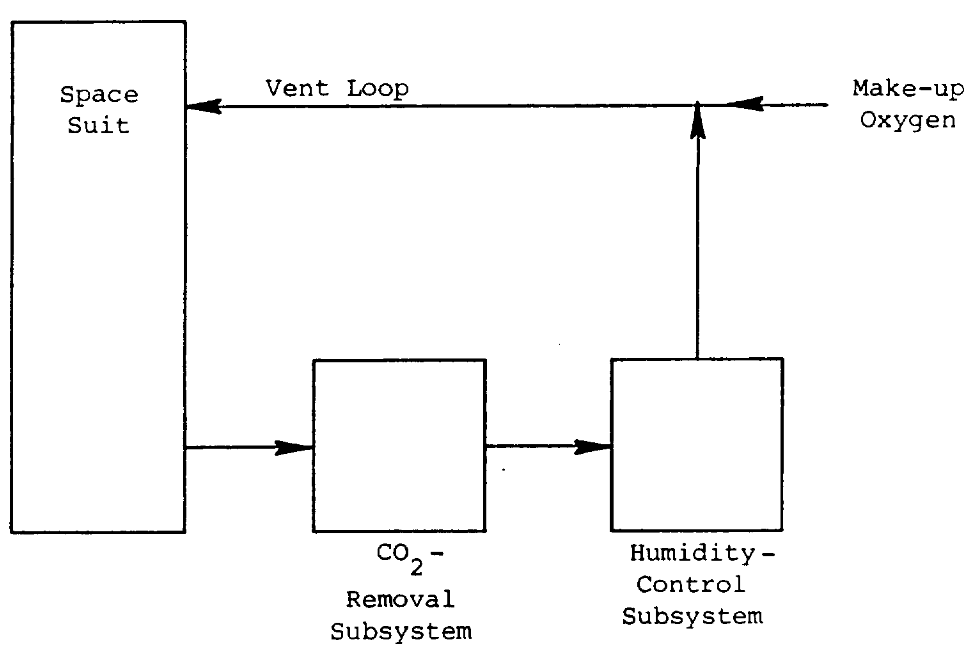

Figure 2.1.-1. General Schematic of the EMU

Table 2.1-I. Design Specifications for the Water-Vapor-Removal Portion of the EMU

Item	Value
Inlet dewpoint temperature, °C (°F)	12.8-29.4 (55-85)
Maximum raffinate dewpoint temperature, °C (°F)	10 (50)
Inlet dry-bulb temperature, °C (°F)	21.1-29.4 (70-85)
System gas pressure, cmHg (psia)	42.9 (8.3)
Vent-loop flow rate, kg/hr (lb/hr)	4.8-7.0 (10.5-15.5)
Water-removal rate range, kg/hr (lb/hr)	0.06-0.24 (0.14-0.53)
Average water-removal rate, kg/hr (lb/hr) (design point)	0.14 (0.3)
Maximum total module volume, m^3 (ft^3)	3.5×10^{-3} (0.125)
Extravehicular activity operation time (hours)	5 (4-hour mission, 1-hour margin of safety)
Inlet CO_2 contact, cmHg (psia)	0-0.76 (0-0.15)

The Electrochemically Regenerable CO_2 Absorbant (ERCA) system uses a liquid alkaline absorbent to control CO_2 and a condenser/heat exchanger and water separator to control humidity.[7,8,9] Many other techniques have been investigated; most are capable of providing reliable control of CO_2 or humidity in the EMU. However, NASA is investigating several alternative technologies that would lower the power requirements and simplify the subsystem.

BRI was recently awarded a Phase I Small Business Innovation Research Contract with NASA to investigate the use of a membrane-based system to remove CO_2 from spacecraft atmospheres (Contract No. NAS 9-18085, entitled "Development of a Liquid-Sorbent/ Membrane Contactor Subsystem for CO_2 Removal"). This system promises to be a lightweight, energy-efficient alternative to the

CO_2-removal systems described above. The membrane-based dehumidification subsystem investigated here could possibly be combined with the membrane-based CO_2-removal subsystem currently under development, and the result would be a lightweight, energy-efficient alternative to the other technologies NASA is considering. We will investigate the feasibility of using such a combination during the Phase I program currently in progress.

2.2. Principles of Membrane-Based Dehumidification

Over the past five years, Bend Research, Inc., has been developing synthetic membranes for dehumidification of various noncondensable gas streams. The membranes used for dehumidification are hydrophilic--that is, they have a high permeability to water vapor and a relatively low permeability to the particular noncondensable gases in the feed stream of interest. This high selectivity* (α) for water vapor results in a membrane that separates water vapor from noncondensable gas, even when the feed-stream partial pressure of the noncondensable gas is much higher than that of water vapor--i.e., when the feed stream has a relatively low dew point.

The rate at which water vapor is removed from an air feed by permeation through the membrane (i.e., the "flux" of water vapor) is directly proportional to the difference in water-vapor partial pressure across the membrane. The water-vapor partial pressure is the product of the mole-fraction of water and the total pressure of each stream. The greater the water-vapor partial-pressure difference across the membrane, the greater the flux of water vapor through the membrane.

When a feed-air stream first enters a dehumidification membrane module, the water-vapor partial-pressure difference across the membrane is at its highest because no water vapor has yet been removed from the air. Thus, the flux of water vapor through the membrane is highest at this point. As water vapor is

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* Selectivity of X over Y = $\dfrac{\text{Permeability of X}}{\text{Permeability of Y}}$, where permeability is the amount of gas transported across the membrane per unit area, unit time, and unit driving force.

removed from the air, the water-vapor partial-pressure difference decreases and is lowest at the exit point of the module, where the air is driest. These factors must be considered when designing membrane-based dehumidification subsystems.

2.3. Membranes Used for Dehumidification

The dehumidification membranes currently under development at Bend Research are of the "thin film composite" (TFC) type. Those composite membranes consist of a very thin skin deposited on a suitable asymmetric porous support membrane such as a flat sheet or hollow fiber. Figure 2.3.-1 shows a scanning electron micrograph (SEM) of a composite hollow-fiber membrane. Here the TFC membrane coated on the inside surface of the hollow-fiber support membrane is too thin (about 0.1 μm thick) to be seen. Figure 2.3.-2 shows a schematic of a TFC membrane. The main

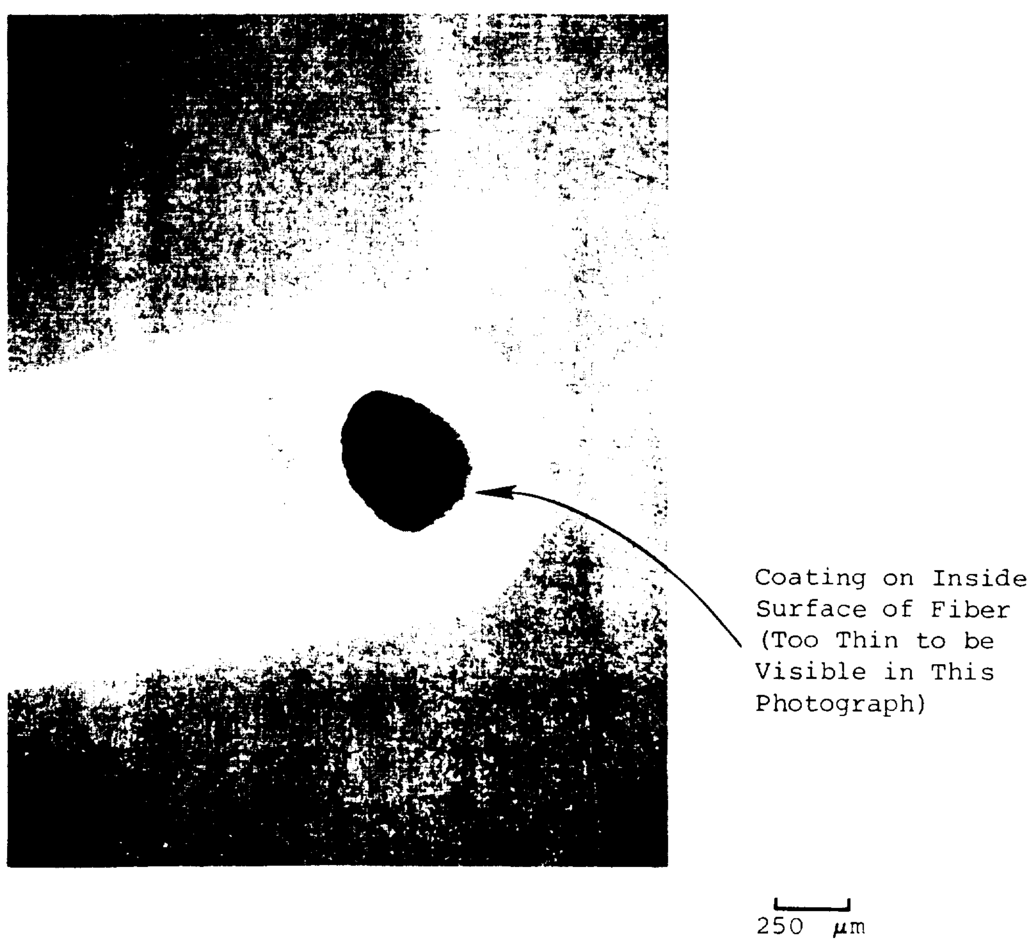

Figure 2.3.-1. SEM of a Hollow-Fiber Membrane

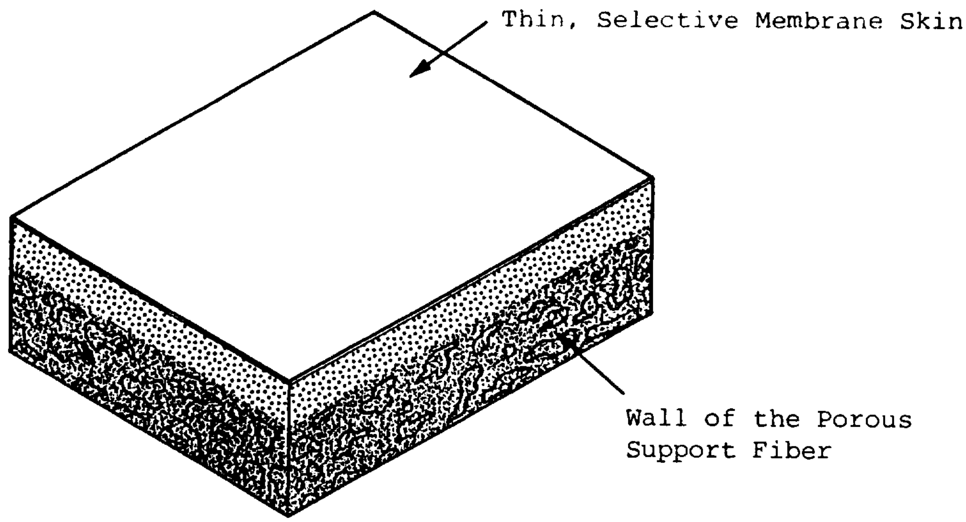

Figure 2.3.-2. Simplified Schematic of a TFC Membrane

skin can be "fine tuned" to yield high selectivity and flux, and 2) the porous support membrane can be optimized separately to minimize its resistance to flow without sacrificing the strength needed to withstand pressurized feed streams.

Specifically, the TFC membranes we are developing are primarily highly crosslinked polyureas and polyamides.[10,11] These membranes are formed by the interfacial polymerization of a monomeric, oligomeric, or polymeric amine precursor with a suitable crosslinker through the process illustrated in Figure 2.3.-3. The microporous support fiber is immersed in an aqueous solution of the amine precursor, thus filling the pores. A solution of a water-immiscible solvent (e.g., hexane) that contains the crosslinking agent is then passed down the lumen of the fiber. The amine precursor reacts with the crosslinker to form a polymer network at the interface between the organic and aqueous phases. This network grows rapidly, creating the permselective layer. The reaction is limited by the formation of this permselective layer because the diffusion of the reactants

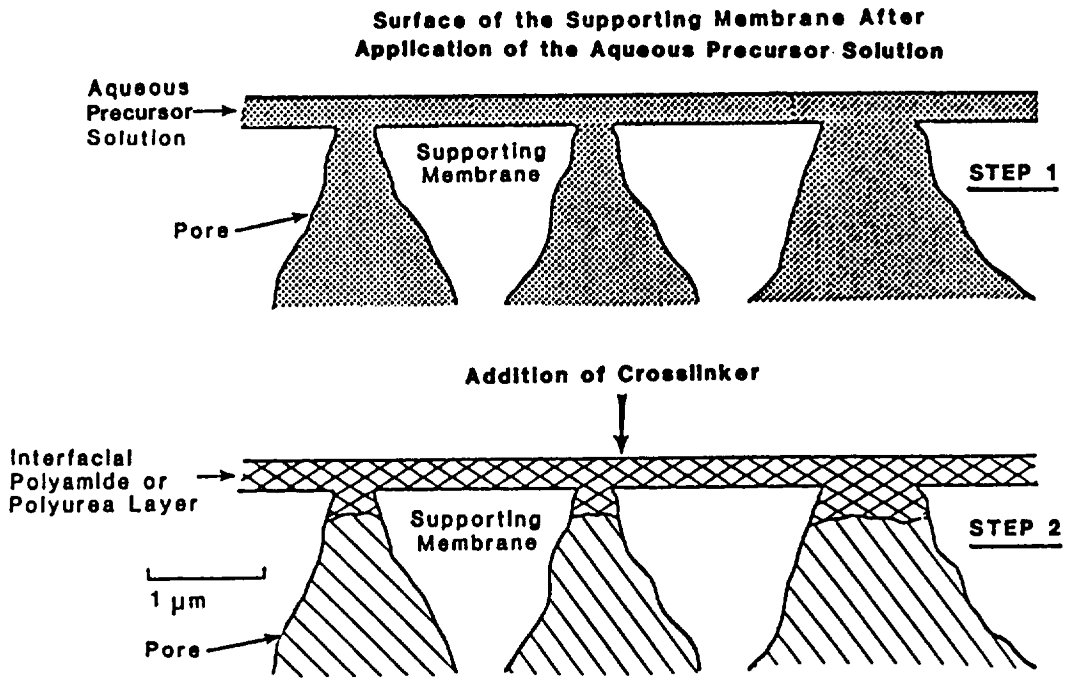

Figure 2.3.-3. Schematic Showing the Formation of a TFC Membrane by Interfacial Polymerization

is greatly hindered by the polymer barrier. The selective barrier layer thus formed is extremely thin as a result of this self-limiting action. Interfacial membranes of many differing chemical structures can be produced. By a judicious choice of precursors, it is possible to obtain membranes that will perform the desired water/air separation.

Selectivity is an important characteristic of the membrane-based dehumidification subsystem under development. Typically, membranes are developed that represent the best compromise between selectivity and water-vapor permeability, since an increase in one parameter usually results in a corresponding decrease in the other. Thus, to obtain membranes with high permeabilities to water vapor, selectivity must, to some extent, be sacrificed.

2.4. Membrane Modules for Dehumidification

A module designed for EMU dehumidification should be inexpensive, compact, and lightweight. To be compact and lightweight, the "packing density," or amount of membrane area per volume of module, must be high. Furthermore, the pressure drop on the feed and permeate sides of the module should be minimized, so that the pressure of the exiting dehumidified air nearly matches that of the feed air--i.e., so the pressure is maintained inside the space suit. Two basic module designs were considered at the beginning of this project: 1) plate-and-frame modules, and 2) spiral-wound modules. The plate-and-frame design was quickly rejected for this application for reasons discussed in Section 2.4.1. Most of our module-development work was then directed at modifying a spiral-wound module specifically for dehumidification applications. Although we obtained promising results with the spiral-wound modules, in the middle of this project a breakthrough in our own hollow-fiber technology prompted us to interrupt the work with spiral-wound modules and to concentrate on developing hollow-fiber modules instead. The reasons for this are explained in Section 2.4.3.

2.4.1. Plate-and-Frame Modules

The plate-and-frame module design, shown schematically in Figure 2.4.-1, consists of a series of membrane "sandwiches," each laminated to a gasket that provides a pressure seal between the ambient and the permeate-side porous spacer material. The coated side of the TFC membrane faces this gasket and spacer. The porous spacer is one that minimizes the pressure drop on the permeate side of the module.

Although the pressure drop in plate-and-frame modules is low, their packing density is low compared with that for other modules, as illustrated in Figure 2.4.-2. Plate-and-frame modules are also more expensive to make than are other modules, and they are relatively heavy. For these reasons we rejected the use of plate-and-frame modules for this application.

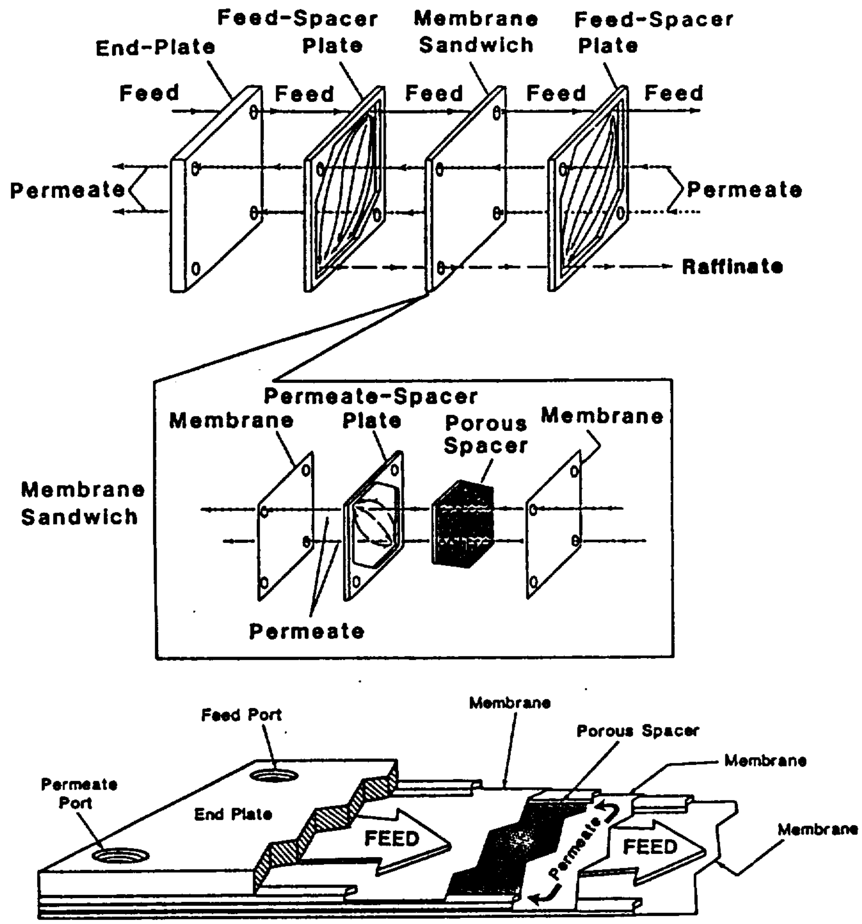

Figure 2.4.-1. Design of Plate-and-Frame Membrane Module

2.4.2. Spiral-Wound Modules

Spiral-wound modules have a higher packing density than do plate-and-frame modules (see Figure 2.4.-2). In addition, they are less expensive and weigh less.

The design of a typical spiral-wound module is sketched in Figure 2.4.-3. Like the plate-and-frame module, this module contains a membrane sandwich. However, in a spiral-wound module this membrane sandwich is rolled up around a permeate-collection tube, forming a tight, compact module. One problem with spiral-wound modules used for dehumidification is that they have a high pressure drop on the permeate side of the module. Although we made considerable progress in developing new designs for spiral-wound modules that minimized this pressure drop, we interrupted

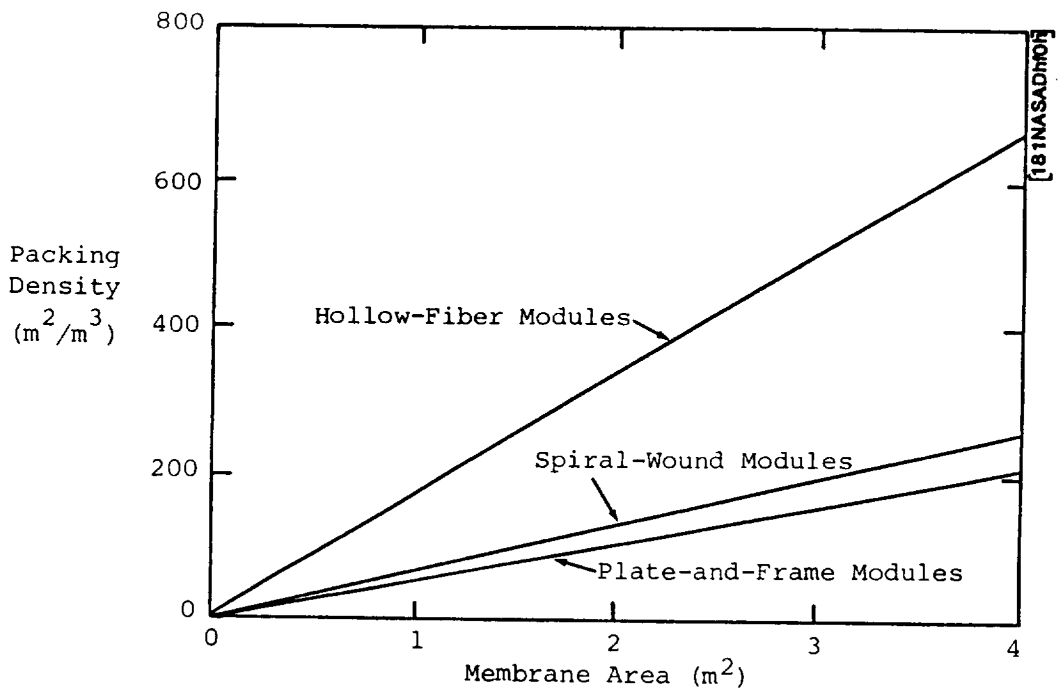

Figure 2.4.-2. Packing Densities of Dehumidification Membrane Modules

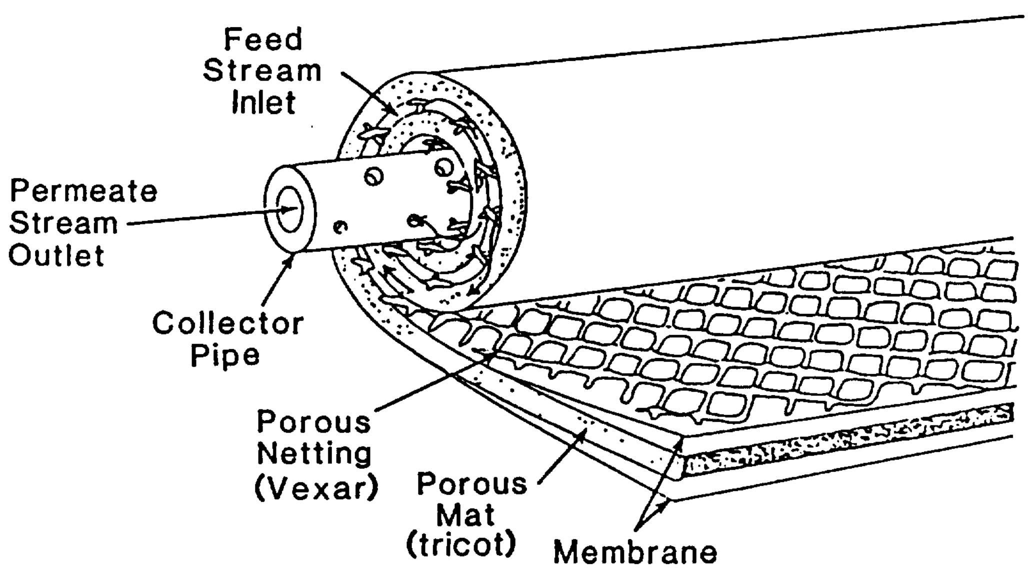

Figure 2.4.-3. Spiral-Wound Module Design

this work in favor of developing a hollow-fiber module for dehumidification.

2.4.3. Hollow-Fiber Modules

As shown in Figure 2.4.-2, hollow-fiber modules have the highest packing density of the three types of modules. These modules can also be made from very lightweight materials. At the beginning of this program, hollow-fiber technology suitable for dehumidification had not been sufficiently developed. No reliable method had been invented to successfully apply the very thin dehumidification-membrane coating to the inside (lumen) surface of the support fibers. However, during this program a breakthrough in TFC hollow-fiber technology achieved under another contract* led to the successful application of dehumidification membranes onto the surfaces of the fiber lumens. This development meant that hollow-fiber modules, with all their advantages, might be developed for this dehumidification application. The design of such a hollow-fiber module is shown in Figure 2.4.-4.

Hollow-fiber membranes have previously been considered by NASA for water-vapor removal.(12) Three membranes were studied: 1) Gore-Tex, a microporous hydrophobic membrane, 2) Bio-Fiber 50, a cellulosic fiber (hydrophilic), and 3) XM-S, a hydrophilic acrylic fiber. All three were eventually rejected for various reasons: The Gore-Tex fiber was hydrophobic and therefore had no detectable water-vapor permeability; whereas the Bio-Fiber 50 ruptured when it dried. The XM-S fibers showed more promise, in that water vapor was removed from the feed stream. However, the measured permeability of the fiber was so low that nearly 30 m^2 of membrane area would be needed to perform the desired separation--an impractically large amount for NASA's application.

* "Onboard Water Generation for Military Vehicles," DOD Contract No. DAAE07-85-C-R059

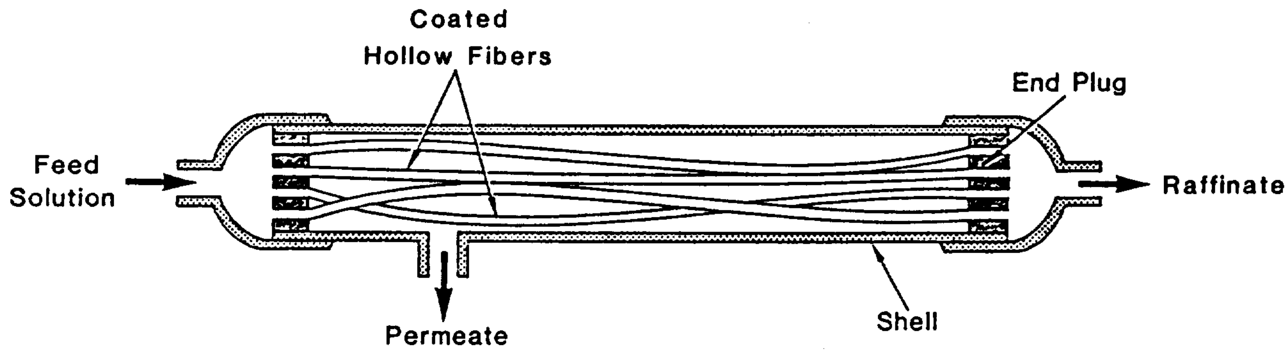

Figure 2.4.-4. BRI Tube-Side-Feed Hollow-Fiber Membrane Module

However, recent developments at BRI have led to hollow-fiber modules with much higher permeability to water vapor. A dehumidification system based on this same technology promises to be effective for NASA's EMU application.

3.0. RESULTS AND DISCUSSION

The goal of this program was to investigate the use of a membrane-based system to control humidity in the EMU. Specifically, our objectives were as follows:

1) To screen dehumidification membranes to identify those that minimize the size, weight, and energy consumption of the membrane-based subsystem
2) To design and fabricate membrane modules containing these membranes
3) To evaluate these membrane modules under the range of operating conditions expected to be encountered during actual use
4) To design a preprototype membrane-based humidity-control subsystem for an advanced EMU application.

All of these objectives were met during this program. Specific results are discussed below.

3.1. Screening of Dehumidification Membranes

The objective of this task was to identify membranes that would minimize the size, weight, and energy consumption of the membrane-based dehumidification subsystem. Table 3.1.-I lists the membranes evaluated in this task, the type of membrane, and the manufacturer or supplier of the membrane.

All screening tests were conducted using a feed stream with a dew point of approximately 31°C and at a pressure of 69.3 cmHg. The permeate side of the membrane was set at 1 cmHg. (These test conditions do not correspond with the specifications given in Table 2.1.-I, because the test apparatus used to perform the screening tests of these flat-sheet membranes had not yet been modified to operate at a feed pressure of 42.9 cmHg.)

The results of the screening tests are given in Table 3.1.-II. These data show that the Disac No. 2 membrane had the best combination of high water permeability and high water-vapor/air selectivity.

Using a computer program developed at BRI that models the dehumidification membrane module, the membrane area required to produce 0.028 standard m^3/min of raffinate at a dew point of 10°C

Table 3.1.-I. Membranes Evaluated in Screening Tests

Membrane	Manufacturer	Membrane Type
CA	Grace Membrane systems, Bend, Oregon	Asymmetric cellulose acetate
CA-SG	Grace Membrane systems	Modified asymmetric cellulose acetate
FT-30-BW	FilmTec Corp., Minneapolis, Minnesota	Polyamide TFC
Disac No. 1	BRI	Proprietary TFC
Disac No. 2	BRI	Proprietary TFC
NS-100	BRI	Proprietary TFC
J-0.5	BRI	Proprietary TFC

Table 3.1.-II. Results of Screening Tests
Feed Conditions: 69.3 cmHg, dew point 31°C
Permeate Conditions: 1 cmHg

Membrane	Water-Vapor Permeability $\left(\frac{10^{-4}\ cm^3}{cm^2\text{-sec-cmHg}}\right)$	Selectivity
CA	56	680
CA-SG	100	900
FT-30-BW	44	100
Disac No. 1	93	250
Disac No. 2	180	900
NS-100	27	21
J-0.5	46	>3000

Table 3.1.-III. Calculated Membrane Area Required to Produce 0.028 Standard m^3/min of Raffinate at a Dew Point of 10°C
Feed conditions: 42.9 cmHg, dew point 29.4°C
Permeate conditions: 1 cmHg

Membrane	Area (m^2)
CA	0.56
CA-SG	0.33
FT-30-BW	0.50
Disac No. 1	0.28
Disac No. 2	0.18
NS-100	0.65
J-0.5	0.88

was calculated based on these data. It is interesting to note that although Membrane J-0.5 had a selectivity of >3000, this membrane requires the most membrane area to perform the separation. This is because very little air permeates a membrane with this selectivity, and thus the driving force for transport of water vapor across the membrane is extremely small.

Thus, based on the tests with flat-sheet membranes, the Disac No. 2 membrane would be ideal for use in the subsystem. However, the chemicals used to make the Disac No. 2 membrane must be synthesized at BRI. During this program, our supplies of raw materials used to make this membrane were exhausted, and a lead time of three months was required to obtain more. Thus, the Disac No. 2 membranes could not be used for the breadboard modules. Additionally, our shift in emphasis to hollow-fiber rather than spiral-wound membranes (discussed below) meant that the replacement for Disac No. 2 had to be available in hollow-fiber form--i.e., either J-0.5 or NS-100 membranes. As discussed above, selectivity of the J-0.5 membrane is too high; thus the NS-100 membrane was used in the breadboard modules.

3.2. Module Design and Fabrication

3.2.1. Introduction

The original intent of this program was to design and fabricate plate-and-frame or spiral-wound modules for use in the dehumidification subsystem. However, results obtained in programs performed concurrently with this program* suggested that hollow-fiber membrane modules could be made that would be more suitable for this application. The key to this change in emphasis was a breakthrough that allowed us to place the dehumidification membrane on the inside surface of hollow-fiber support membranes.

As has been discussed, the key advantage of using hollow-fiber membrane modules is their high packing density. Additionally, the hollow-fiber modules have a much lower pressure drop on the permeate side of the membrane, allowing for better control over the permeate-side conditions.

The objectives of this task, then, were to first optimize the hollow-fiber dehumidification membrane and to then construct three breadboard hollow-fiber dehumidification modules.

3.2.2. Optimization of Hollow-Fiber Membranes

The goal of this task was to optimize the hollow-fiber dehumidification membranes. The approach used in this task was to 1) determine the appropriate dimensions of the hollow-fiber support membranes, 2) optimize the morphology of the support fibers, and 3) optimize the dehumidification membrane placed on the inside surface of the fibers. Specific results are discussed below.

3.2.2.1. Determination of Fiber Dimensions

The purpose of this task was to determine the dimensions of the hollow-fiber support membranes that would result in the optimal module design for dehumidification

* "Onboard Water Generation for Military Vehicles," DOD Contract No. DAAE07-85-C-R059. "Development of a Membrane-Based Compressed-Air Dehydration," DOD Contract No. N00167-88-C-0026.

applications. Specifically, the ideal inside diameter of the fiber had to be identified. The fibers initially tested in this program were originally developed for reverse-osmosis applications. The inside diameters of these polyethersulfone fibers are approximately 0.03 cm. The thickness of the fiber wall is about 0.02 cm. These TFC hollow-fiber membranes, patented by BRI, have a very thin membrane coating (about 0.1 micron thick) placed on the inside of the fiber. The fiber provides mechanical support for the coating, which is tailored for the desired selectivity. These fibers were made with a relatively small internal diameter, which is necessary for fibers operated at high pressures (up to 50 atm). As such they were not optimal for use in the EMU--i.e., the pressure drop down the length of the hollow-fiber module would be about 2 cmHg under the conditions required. If used in the EMU, a blower would be required to overcome this pressure drop, resulting in a dramatic increase in weight and energy consumption.

The pressure drop through a hollow-fiber module can be reduced by increasing the diameter of the fibers, as shown in Figure 3.2.-1. The decrease in pressure drop would result in a corresponding decrease in energy required to overcome this pressure drop, as shown in Figure 3.2.-2. This analysis suggests that fibers with large internal diameters should be used for this application. However, as the diameter of the fiber is increased, the volume of a module containing a fixed amount of membrane area also increases, as shown in Figure 3.2.-3. Thus, the optimal internal diameter for the hollow fibers will be a compromise between module volume and energy consumption. Based on this analysis, we believe the optimal diameter for the hollow fibers to be 0.1 to 0.2 cm.

3.2.2.2. <u>Optimization of Hollow-Fiber Support Membranes</u>

The purpose of this task was to optimize the hollow-fiber support membranes for dehumidification applications. The success of this task depended on fabricating hollow-fiber membranes with internal diameters of 0.1 to 0.2 cm (3 to 7 times larger than we had previously fabricated) that also had high

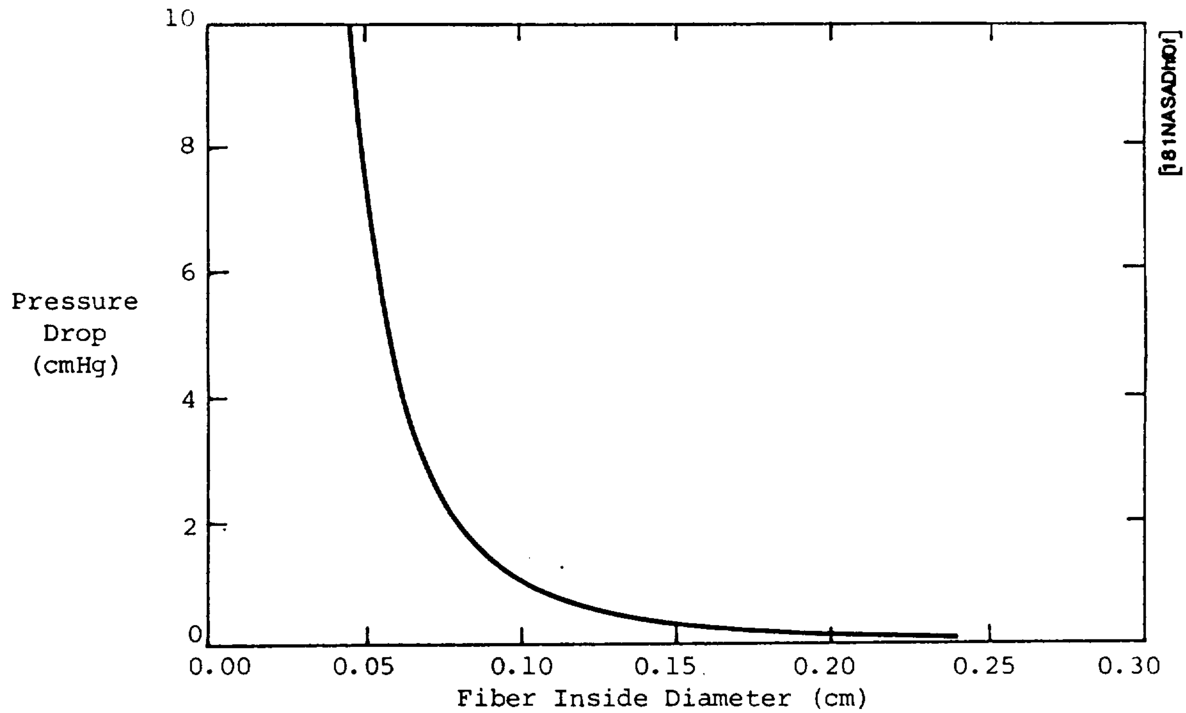

Figure 3.2.-1. Pressure Drop Down the Length of a Hollow-Fiber Module as a Function of the Inside Diameter of the Fibers (module is 46 cm long)

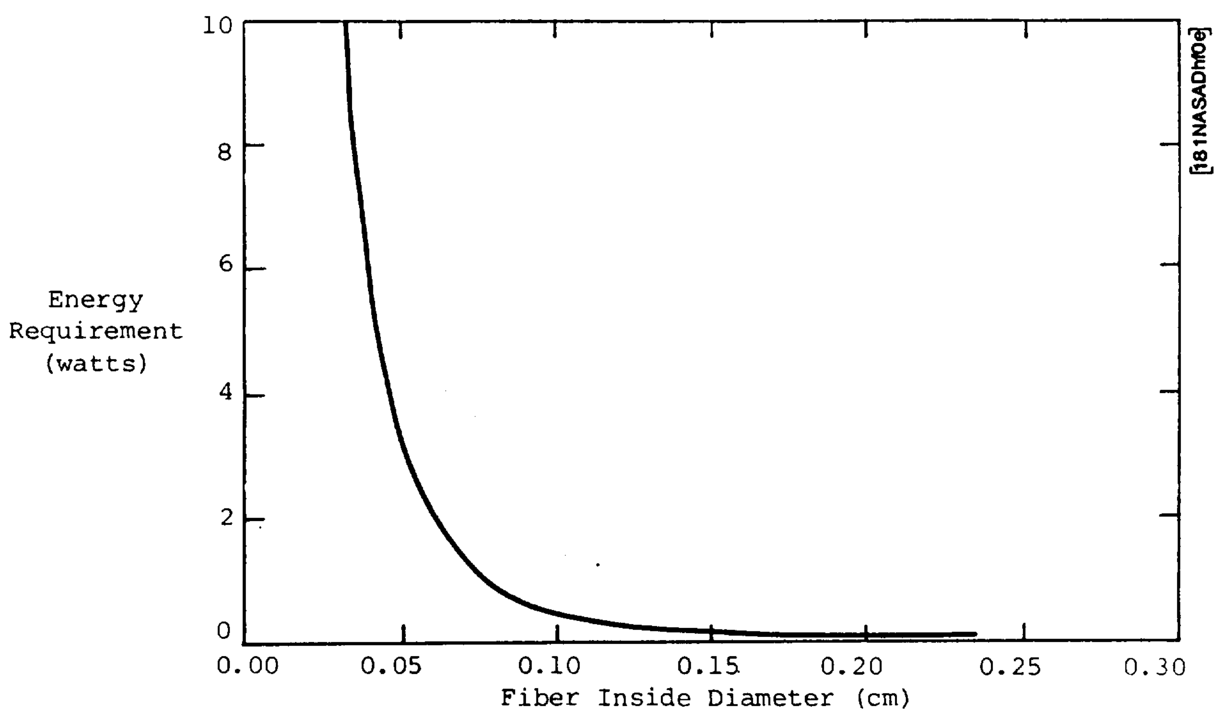

Figure 3.2.-2. Energy Required of a Hollow-Fiber Module as a Function of the Inside Diameter of the Fibers (module is 46 cm long)

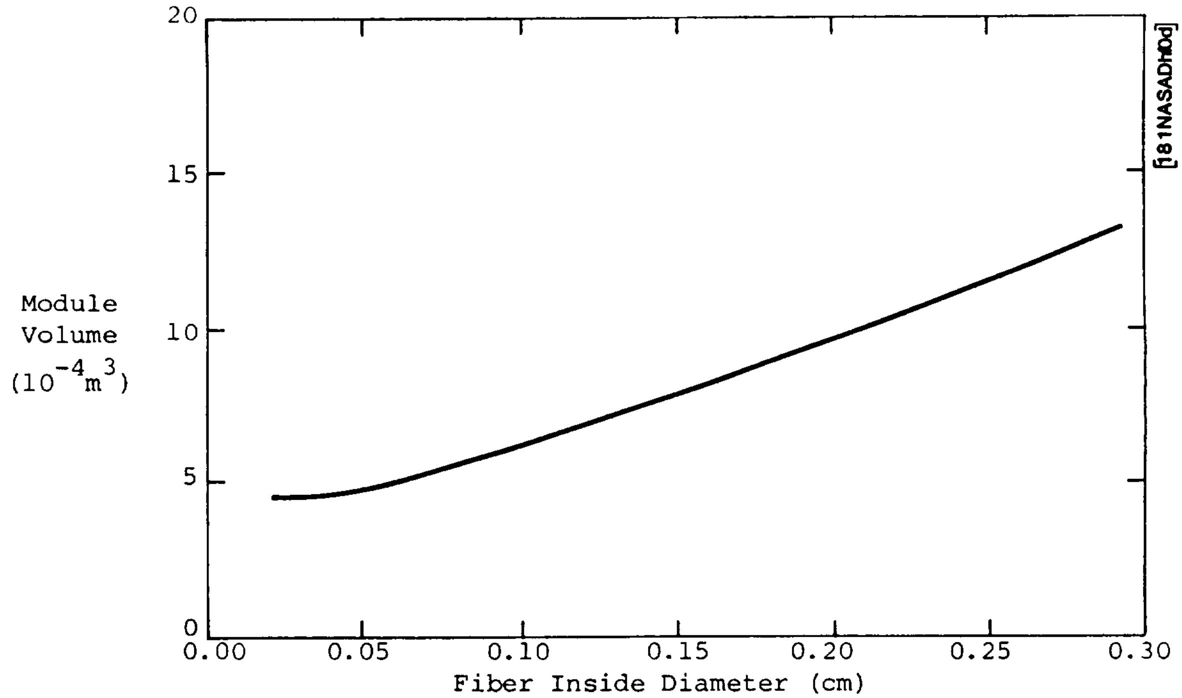

Figure 3.2.-3. Volume of a Hollow-Fiber Module as a Function of the Inside Diameter of the Fibers (module is 46 cm long)

porosity. The fibers also needed to have smooth lumen surfaces to allow for uniform coating by the TFC membrane, as well as sufficient strength to assure long lifetimes. We successfully accomplished this task within the limited time of this program.

Two tests were used to evaluate the fibers made in this program--the permeability of the uncoated fiber to nitrogen (an indication of the porosity of the fiber and predictor of water-vapor permeability) and the burst pressure of the fiber (an indication of the strength and durability of the fiber). Table 3.2.-I lists the characteristics of the hollow fibers made in this program. These data show two things. First, by manipulation of the conditions used to make fibers, we were able to increase the nitrogen permeability of the fibers by almost an order of magnitude. Second, the nitrogen permeability of the fibers could be further increased by using a fiber-posttreatment

Table 3.2.-I. Characteristics of Hollow Fibers Developed in this Program

Fiber Batch	Posttreatment	Internal Diameter (cm)	Nitrogen Permeability $\left(\frac{10^{-4}\ cm^3}{cm^2\ sec\text{-}cmHg}\right)$	Burst Pressure (atm)
P80811	No	0.11	18	13.6
P80812A	No	0.09	5	7.8
	Yes	0.09	22	7.8
P80812B	No	0.11	3	7.8
	Yes	0.11	12	9.2
P80823A	No	0.10	2	8.5
	Yes	0.10	8	8.5
P80823B	No	0.12	0.2	10.8
	Yes	0.12	20	10.8
P80824A	Yes	0.12	1	11.2
P80824B	No	0.12	36	10.2
	Yes	0.13	120	13.6
P80825A	No	0.10	44	11.9
	Yes	0.10	86	13.6
P80825B	No	0.13	84	13.6
P80826	No	0.12	1	9.5
	Yes	0.12	18	10.8
P80830	No	0.14	1	7.8
	Yes	0.14	24	9.9
P80907	No	0.13	175	9.9
	Yes	0.13	175	10.5
P81020	No	0.14	62	8.8
	Yes	0.14	81	10.2
P81118	No	0.13	20	11.2
	Yes	0.13	105	13.3
P81122	No	0.13	52	11.2
	Yes	0.13	106	13.6

process developed in a previous program at BRI.* Based on these results, Fiber Batch P80907 would be optimal for the dehumidification modules. Figure 3.2.-5 shows an SEM of a cross section of these fibers.

However, although the nitrogen permeability of the uncoated fiber can be used as one predictor of the water-vapor permeability of the coated fiber, it is not the only criterion. In addition to nitrogen permeability, the inside surface of the fiber must be sufficiently smooth to assure a uniform coating of the dehumidification membrane. Therefore, small-scale modules (56 cm^2) were made from several of the fiber batches, coated with the Disac No. 1 dehumidification membrane, and evaluated in a gas-permeation test. The test was used to determine the extent to which the fibers were coated with the Disac No. 1 membrane.

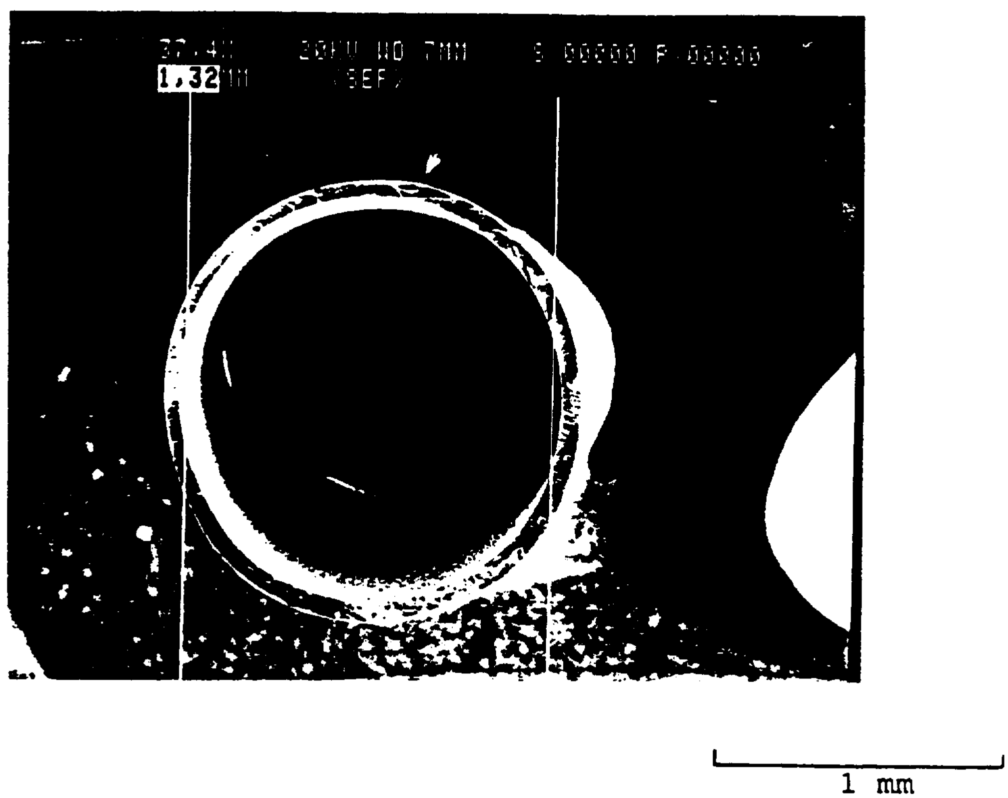

Figure 3.2.-5. SEM of a Cross Section of Fibers from Batch P80907

* "Chlorine-Resistant Hollow-Fiber Reverse-Osmosis Membrane Elements," DOD Contract No. DAAK-70-85-C-0059

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In previous work we found that this membrane has a selectivity of oxygen over nitrogen of about 1.5 or higher. Thus, if the selectivity of the coated fiber was 1.5, the coating was uniform and the fibers acceptable for use. The results of this test are given in Table 3.2.-II. These results show that selectivity of the coated fibers to oxygen over nitrogen was indeed above 1.5 in all cases. This indicates that there was a uniform coating on the surface of the fibers, and all of the fiber batches evaluated were acceptable for use in the program.

Based on these results, several additional small-scale modules were constructed and tested on the dehumidification apparatus. These results are presented in Table 3.2.-III. Three types of dehumidification membranes were used in this test: the

Table 3.2.-II. Results of Gas-Permeation Tests of Small-Scale Hollow-Fiber Modules (56 cm^2) Coated with the Disac No. 1 Dehumidification Membrane Coated Fiber

Fiber Batch*	Module Designation	Uncoated Fiber N_2 Permeability $\left(\frac{10^{-4}\ cm^3}{cm^2\text{-sec-cmHg}}\right)$	Permeability $\left(\frac{10^{-4}\ cm^3}{cm^2\text{-sec-cmHg}}\right)$		Selectivity $\frac{O_2}{N_2}$
			O_2	N_2	
P80823B	A	20	0.64	0.40	1.6
	B	20	0.67	0.42	1.6
P80825A	A	86	4.9	2.5	2.0
	B	86	3.9	2.1	1.9
P80826	B	18	3.4	1.9	1.8
	C	18	3.4	1.8	1.9
P80830	E	24	0.46	0.23	2.0
	F	24	0.40	0.19	2.1
P80907	D	175	0.99	0.66	1.5
	E	175	1.90	1.27	1.5

* All fibers were posttreated

Table 3.2.-III. Results of Dehumidification Tests With Small-Scale Hollow-Fiber Modules

Feed Conditions: 69.3 cmHg, dew point 29.4°C
Permeate Conditions: 1 cmHg

Fiber Batch**	Module Designation	Water-Vapor Permeability $\left(\frac{10^{-4}\ cm^3}{cm^2\ sec\text{-}cmHg}\right)$	Selectivity $\frac{H_2O}{Air}$
P80825A	4*	58	520
	7*	81	720
P80825B	1*	38	52
	3*	32	140
P80826	1*	38	35
P80830	1*	39	120
P80907	1*	74	420
	3*	52	303
	7*	100	750
	36+	89	1700
	45++	130	230
	46++	140	230

* Disac No. 1 coating
** All fibers were posttreated
\+ NS-100 membrane
\++ Disac No. 2 coating

two variations of the Disac membrane and the NS-100 membrane. As discussed in Section 3.1., the chemicals used to make the Disac membrane became unavailable at the time these tests were conducted. Thus, we also examined the use of the NS-100 membrane for this application. The results in Table 3.2.-III show that hollow-fiber membrane modules with high water-vapor permeabilities and high selectivities for water vapor over air can be made.

Using our computer modeling program, the area required to treat 7 kg/hr of air with a dew point of 29.4°F at 42.9 cmHg (the design specifications for the EMU) was calculated for each module. The results of these calculations are presented in Table 3.2.-IV and suggest that Fiber Batch P80907 coated with the posttreated Disac No. 2 membrane is optimal for use in the dehumidification subsystem. A module containing about 0.4 m^3 of membrane area would be sufficient for the application of interest. However, since the Disac membrane became unavailable, the NS-100 membrane was used in the breadboard modules. The results in Table 3.2.-IV indicate that NS-100 dehumidification modules should contain 0.7 m^2 of membrane area to perform the desired separation.

Table 3.2.-IV. Calculated Membrane Area Required

Feed Conditions: 7 kg/hr, 42.9 cmHg, dew point 29.4°C
Raffinate Conditions: dew point 10°C
Permeate Conditions: 1 cmHg

Fiber Batch	Module Designation (See Table 3.2.-III)	Membrane Area (m^2)
P80825A	4	1.0
	7	0.74
P80825B	1	1.3
	3	1.74
P80826	1	1.31
P80830	1	1.4
P80907	1	0.80
	3	1.10
	36	0.70
	45	0.43
	46	0.40

3.2.3. Construction of Breadboard Modules

The purpose of this task was to construct three breadboard modules to be used during the remainder of the program. The results presented in the previous section indicated that the modules should contain 0.7 m^2 of membrane area. Fiber Batch P80907 coated with the NS-100 membrane was used in the modules. Table 3.2.-V lists the physical characteristics of these modules. Note that the module volume (2.9×10^{-3} m^3) is less than the goal set by NASA (3.5×10^{-3}).

Prior to using these modules in the breadboard tests (see Section 3.3.), they were evaluated in our standard gas-permeation tests. The results of these evaluations are given in Table 3.2.-VI. Note that Module C was never tested on the dehumidification apparatus. As will be discussed in Section 3.3, this module was used only as a growth medium for microbiological studies.

3.2.4. Conclusions Regarding Module Design and Fabrication

Hollow-fiber membrane modules were optimized for use in the EMU. The optimal internal diameter for the hollow fibers was determined to be from 0.1 to 0.2 cm. The hollow fibers were then optimized such that they had the best combination of high porosity and high strength. Using these optimized hollow fibers, three breadboard-scale dehumidification modules were constructed.

Table 3.2.-V. Physical Characteristics of the Breadboard Modules

Characteristic	Value
Membrane area (m^2)	0.7
Module volume (m^3)	2.9×10^{-3}
diameter (m)	0.076
length (m)	0.46
Weight (kg)	1.8

Table 3.2.-VI. Performance of Breadboard Modules

Module Designation	Gas-Permeation Test*		Dehumidification Test**	
	Oxygen Permeability $\left(\frac{10^{-4}\ cm^3}{cm^2\text{-sec-cmHg}}\right)$	Selectivity $\frac{O_2}{N_2}$	Water Permeability $\left(\frac{10^{-4}\ cm^3}{cm^2\text{-sec-cmHg}}\right)$	Selectivity $\frac{O_2}{N_2}$
A	0.013	1.3	53	4500
B	0.014	1.2	59	4700
C	0.010	1.7	--	--

* Test Conditions: Pure gas at 0.7 atm
** Test Conditions: Feed: 69.3 cmHg, dew point 30°C
Permeate: 1 cmHg

3.3. Testing of Breadboard Modules

The purpose of this task was to evaluate the breadboard-scale hollow-fiber dehumidification membrane modules under conditions expected to be present in the EMU. Three sets of tests were conducted: 1) long-term tests, 2) parametric tests, and 3) microbiological tests. The results of these tests were then used to design a preprototype membrane-based dehumidification subsystem.

3.3.1. Test Plan

The test plan used during this task was as follows. Two modules were tested 7 hours per day, 5 days a week for 90 days. One module--the "parametric test module" (Module B)--was subjected to a variety of feed conditions. The other module--the "long term module" (Module A)--was kept at "baseline" conditions for 2 of the 5 days and at the same conditions as those of the parametric test module the rest of the time. Table 3.3.-I lists

Table 3.3.-I. Conditions Used to Test the Breadboard Modules

Test Condition	Pressure (cmHg)		Feed Dew Point (^{o}C)	Feed-Flow Rate (kg/hr)
	Feed	Permeate		
#1 (baseline)	42.9	0.5	24	4.8
#2	42.9	0.5	29	7.0
#3	42.9	0.5	13	4.8

the conditions used during these tests. The performance of these two modules was monitored over time.

The third module (Module C) was used for microbiological growth studies. This module was kept in the same environment as the other two modules but was not operated on the feed stream. Cultures were taken on the permeate side of the module and sent to NASA-JSC for analysis.

3.3.2. Results and Discussion

Figure 3.3.-1 shows the performance of the parametric test module. Here the rate of water recovery is plotted as a function of time. These data show that reliable, long-term performance can be obtained using the hollow-fiber dehumidification membrane module. Under baseline conditions, the module removed about 0.11 kg/hr of water from the feed stream. Although NASA has specified a water-recovery rate of 0.14 kg/hr, the rate of water removal can be increased by simply increasing the membrane area in the module. Based on these results, we estimate that a module containing 1 m^2 of membrane area (having a volume of only 2.9×10^{-3} m^3) would be required.

Figure 3.3.-2 shows the rate of water recovery by the long-term module as a function of time. Again, as with the parametric test module, long-term reliable performance was obtained. The module removed about 0.11 kg/hr of water from the feed air. The

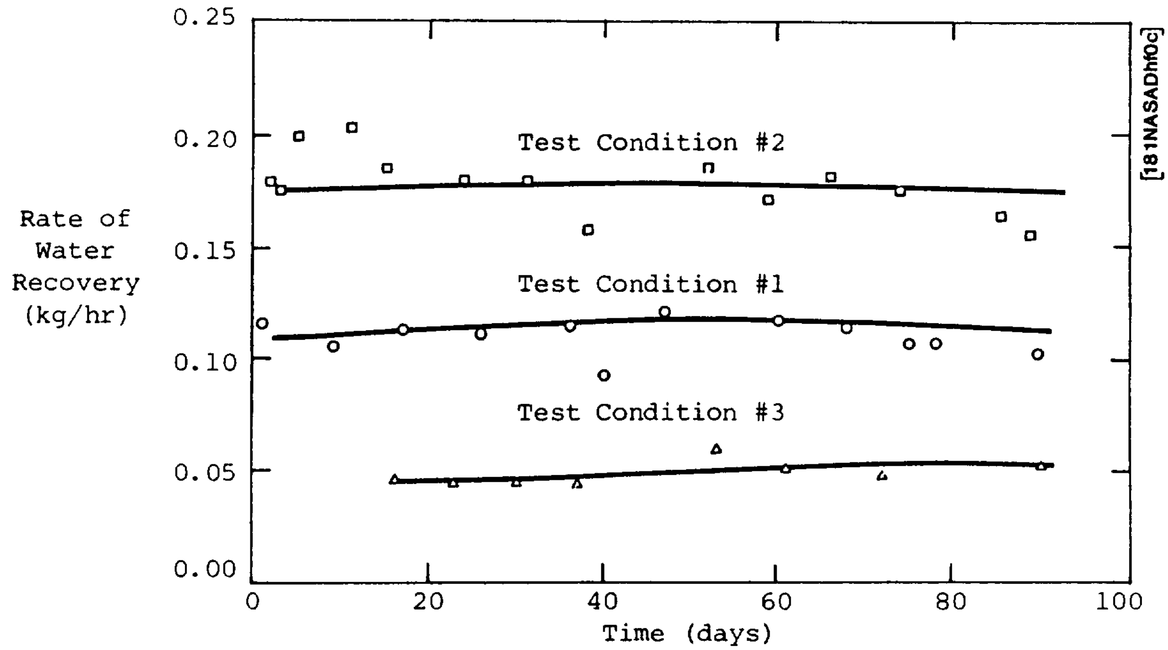

Figure 3.3.-1. Performance of the Parametric Test Module as a Function of Time
Test Conditions: see Table 3.3.-I

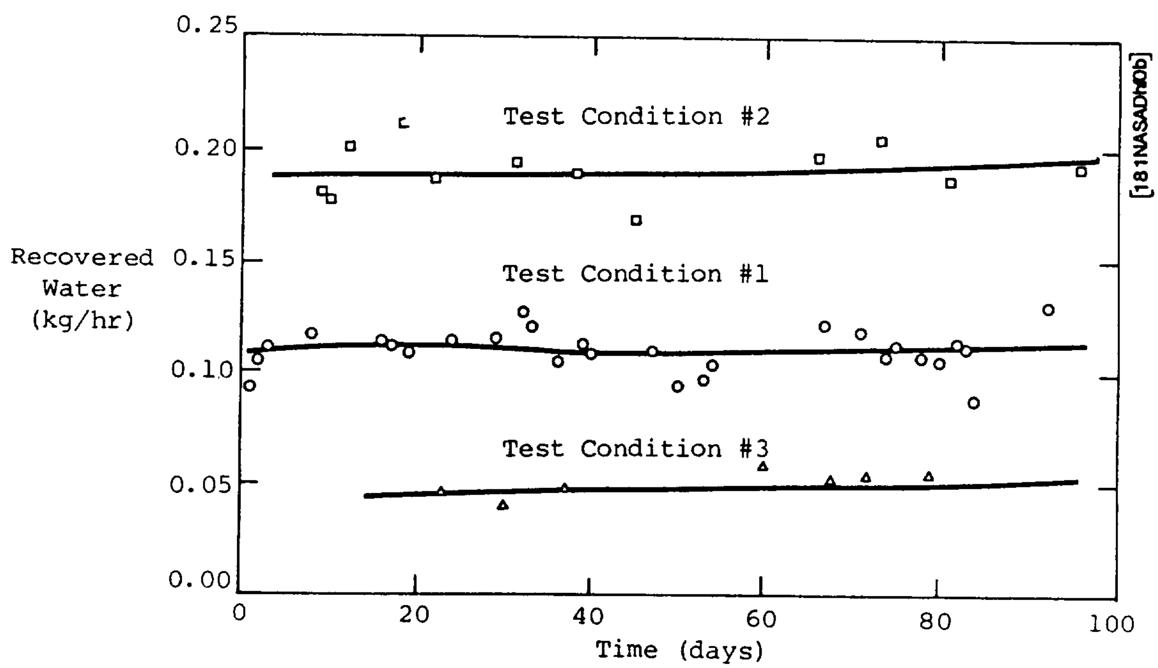

Figure 3.3.-2. Performance of Long-Term Module as a Function of Time
Test Conditions: see Table 3.3.-I

long-term module and the parametric test module exhibited nearly the same performance over the 90-day test.

Because the dehumidification membranes used in this program may be selective to CO_2, we examined the feasibility of using the dehumidification membranes for controlling CO_2 in the EMU. Table 3.3.-II lists the pure-gas permeabilities and selectivities of the parametric test module to oxygen, nitrogen, and carbon dioxide. These results indicate that the NS-100 membrane has a CO_2/N_2 selectivity of only 1.5. Using these permeabilities, we estimated that less than 2% of the CO_2 in the feed stream would permeate the dehumidification membrane module.

To verify this, we tested the parametric test module on a humidified feed stream that had been made using air containing 16% CO_2. The concentration of CO_2 was measured in the feed and permeate from the dehumidification module using a gas chromatograph. As expected, the permeate contained the same concentration of CO_2 as did the feed. However, since less than 1% of the feed-air stream passes through the membrane, only insignificant amounts of CO_2 are removed by the module. Thus, control of CO_2 using these membranes would be impractical.

The results of the microbiological tests performed with the third module were unavailable at the writing of this report. These tests were being performed at NASA-JSC. As soon as the

Table 3.3.-II. Performance of the Parametric-Test Module
Test Conditions: Pure gas at 0.7 atm

Permeability $\left(\frac{10^{-4}\ cm^3}{cm^3\text{-sec-cmHg}}\right)$			Selectivity		
O_2	N_2	CO_2	O_2/N_2	CO_2/O_2	CO_2/N_2
0.014	0.012	0.018	1.2	1.3	1.5

results are available, a summary of these tests will be sent to the Technical Contract Monitor for this program (Ms. Mariann Brown, NASA-JSC).

3.3.3. Conclusions Regarding Breadboard-Module Testing

The results of the tests with the breadboard modules show that long-term, reliable performance can be achieved using hollow-fiber dehumidification membrane modules. The membrane modules consistently removed water vapor from air under the range of conditions expected to be encountered in the EMU.

3.4. Design of a Preprototype EMU-Dehumidification Subsystem

The purpose of this task was to use the data presented in Sections 3.2. and 3.3. to design a preprototype dehumidification subsystem for use in the EMU. The specifications for the EMU (see Table 2.1.-I) were used as a guide in our design. Our objective was to design the subsystem to meet those specifications under "worst case" conditions. However, the infinite number of possible EMU conditions make it difficult to ensure that the subsystem will meet the specifications at all times.

Based on our computer model of the dehumidification membrane module, we chose the conditions shown in Table 3.4.-I as the basis for our design. Only extensive testing of the preprototype

Table 3.4.-I. Design Basis for the Preprototype Dehumidification Subsystem

Item	Value
Feed-flow rate, kg/hr (lb/hr)	4.8 (10.5)
Inlet dew point, ^{o}C (^{o}F)	13 (55)
Raffinate dew point, ^{o}C (^{o}F)	10 (50)
Feed pressure, cmHg (psia)	42.9 (8.3)
Permeate pressure, cmHg (psia)	0.5 (0.1)

subsystem will verify that these are indeed the "worst case" conditions.

Figure 3.4.-1 shows a schematic of the preprototype dehumidification subsystem designed using the "worst case" conditions selected. Table 3.4.-II gives specific details of the various components of the subsystem. For the off-the-shelf system, weights, volumes, and energy requirements for the subsystem were estimated from literature supplied by the manufacturers. Values for the flight-qualified system were estimated from information supplied by NASA. The hollow-fiber membrane module contains 1 m^2 of membrane area and has a volume of only 2.9 x 10^{-3} m^3. The module would have a weight of 1.8 kg.

The total weight and volume of the subsystem will depend on whether other components present in the EMU can be used in the dehumidification subsystem. For example, a blower will be used

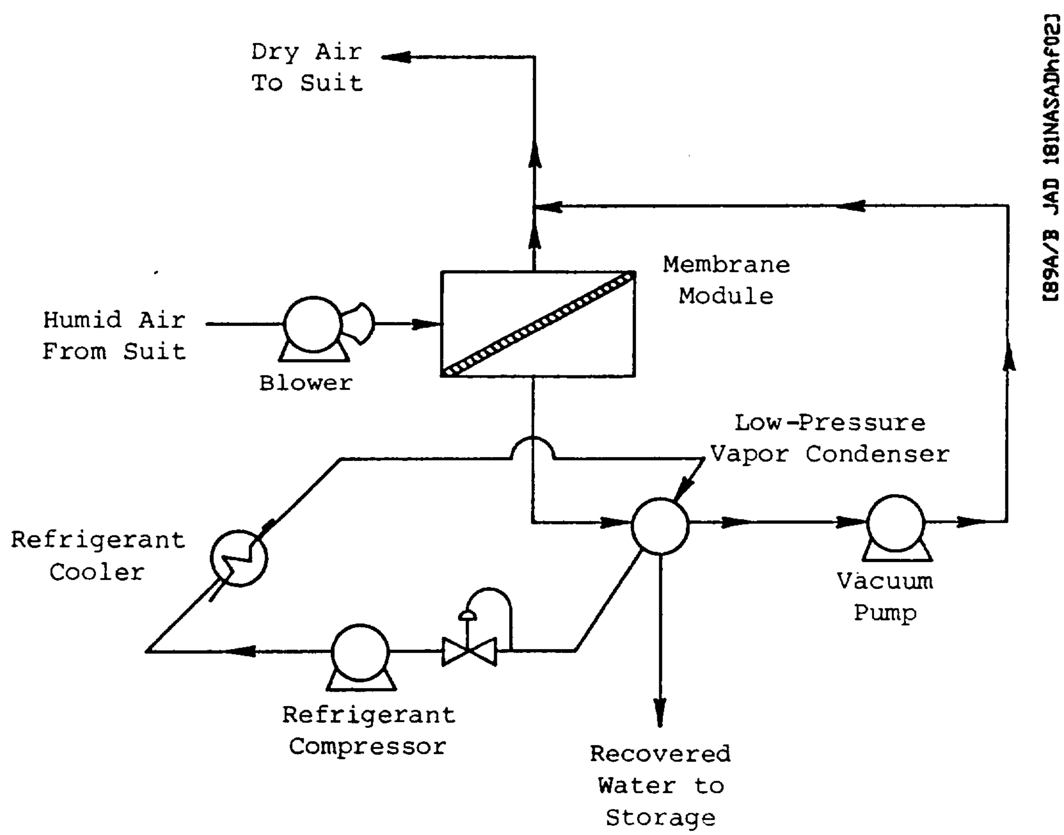

Figure 3.4.-1. Schematic of the Preprototype Dehumidification Subsystem

Table 3.4.-II. Characteristics of the Components of the Preprototype Dehumidification Subsystem

Component	Weight (kg)	Volume (10^{-3} m^3)	Power Requirement (watts)
Off-The-Shelf Components			
Membrane module	1.8	2.9	--
Blower	2.3	0.89	50
Water-vapor condenser	1.4	0.35	--
Vacuum pump	6.8	7.1	500
Refrigerant compressor	6.8	10.5	300
Refrigerant condenser (air-cooled)	2.3	4.2	50
Control system **	----	--	--
Total Off-The-Shelf	21.5	2.6	900
Estimated flight-qualified hardware			
Membrane module	0.91	2.0	--
Blower*	0.45	0.2	10*
Water-vapor condenser	0.45	0.1	--
Vacuum pump	0.91	0.3	50
Refrigerant compressor*	0.91	0.7	100*
Refrigerant condenser*	0.91	0.5	10*
Control system	1.46	0.8	--
Total System	6.00	4.6	170*

* The use of other EMU system components would dramatically lower the power requirements.

** Control system values undetermined at this time.

to circulate air through the vent loop of the EMU. This blower will also be sufficient to circulate air through the hollow-fiber dehumidification module. Thus, the energy and weight of the blower should not be included in the prototype dehumidification subsystem. Additionally, a refrigeration system will be used to lower the air temperature in the space suit as needed. Thus, the weight, volume, and power associated with the refrigeration system need not be included in the preprototype subsystem. Thus, the characteristics of the subsystem given in Table 3.4.-II should be considered "worst case" values.

Using these worst-case values, the weight and volume of the membrane-based subsystem are compared with those of subsystems based on conventional technology in Table 3.4.-III. This analysis shows that the membrane-based subsystem has a clear advantage over the other systems being considered for use in the EMU.

Using our modeling program, the rate of water vapor removed by the subsystem was calculated for feed-air flows of 4.8 and 7.0 kg/hr. The results of these calculations, presented in Figure 3.4.-2, show that the preprototype subsystem will meet or exceed the design specifications. We are confident that a subsystem fabricated to these specifications will be effective in controlling humidity in the EMU.

Table 3.4.-III. Characteristics of Dehumidification Subsystems

Subsystem	Characteristic	
	Weight (kg)	Volume (10^{-3} m^3)
Membrane-based system*	6	4.6
HCCS**	33.8	26
ERCA+	20.4	15

* From this work
** From Reference 4 and 6
\+ From Reference 8 and 9

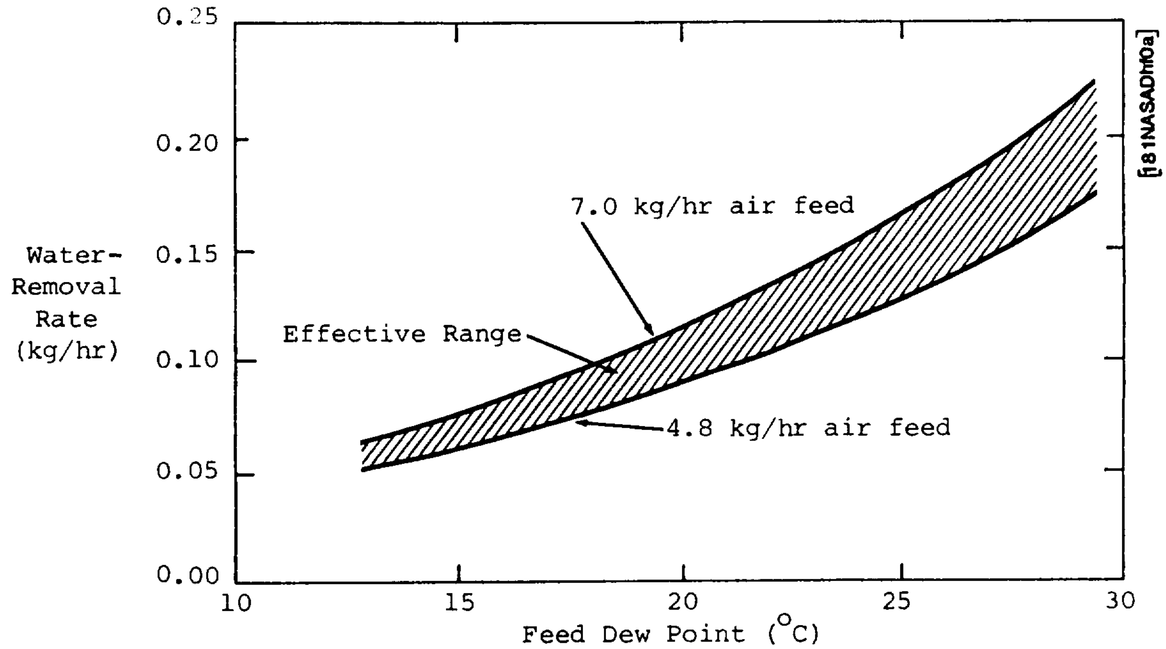

Figure 3.4.-2. Estimated Rate of Water Removal as a Function of the Feed-Air Dew-Point Temperature for the Preprototype Subsystem

4.0. CONCLUSIONS AND RECOMMENDATIONS

This program was highly successful. Novel hollow-fiber dehumidification membranes were developed that efficiently remove water vapor from air under the range of conditions expected to be present in the EMU. During a 90-day test, the performance of the hollow-fiber dehumidification membrane modules remained essentially constant, indicating that long-term reliable performance is feasible with this new technology.

The original intent of this program was to design and fabricate spiral-wound modules for use in the dehumidification subsystem. However, a breakthrough in hollow-fiber technology led to the development of dehumidification modules that are far more suitable for use in the EMU. The two key advantages of using hollow-fiber membrane modules are 1) their high packing density, which allows more membrane area to be packaged into the same volume than other module designs; and 2) their low permeate-pressure drop, which increases the driving force for transport of water vapor across the membrane--a condition that is crucial for good module performance. Figure 4.-1 shows the volume of the

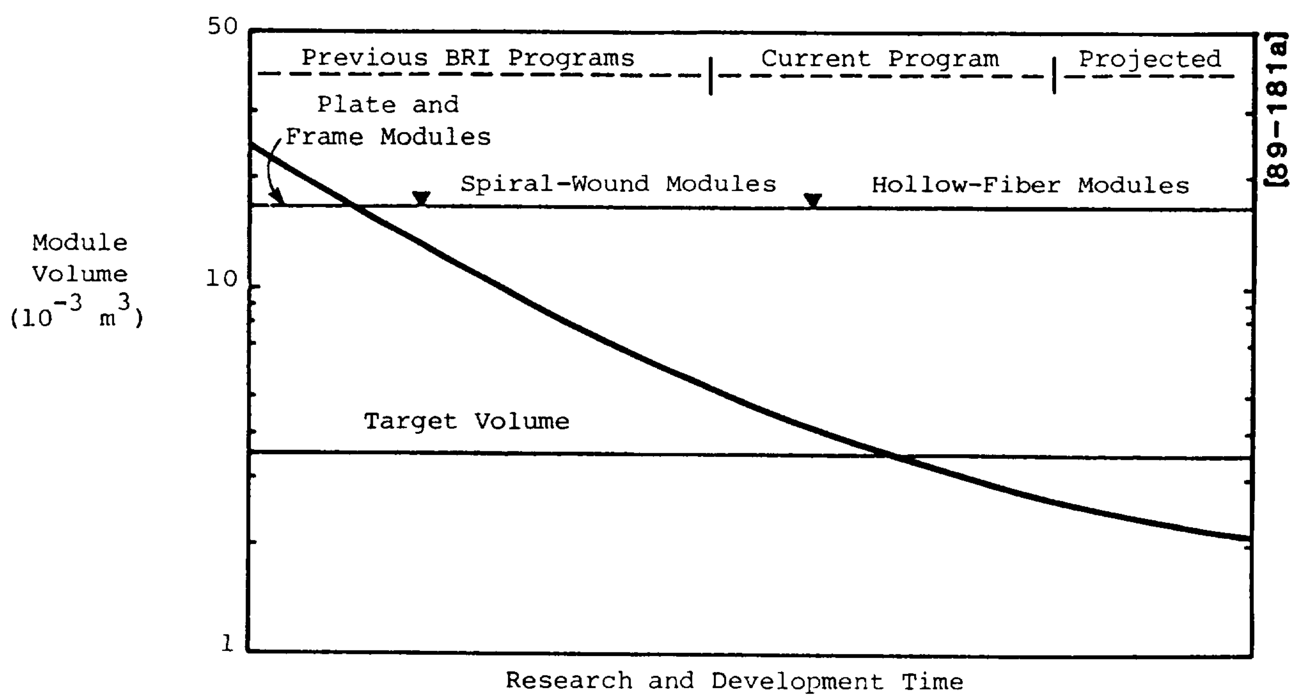

Figure 4.-1. Volume of Membrane Module Required for the EMU as a Function of Research and Development Time

membrane module required for the EMU as a function of time. In previous work at BRI, plate-and-frame and spiral-wound modules were considered for use in dehumidification of spacecraft cabins and in the EMU. However, the volume of the modules was large--well above the target volume of 3.5×10^{-3} m^3 set by NASA. Indeed, at the start of the current program the volume of the module was estimated to be about 5×10^{-3} m^3. Because of the development of the hollow-fiber technology, by the end of this program the module volume was 2.9×10^{-3} m^3--well within the goal set by NASA. With further work, we are confident that this volume can be reduced to at least 2.0×10^{-3} m^3.

A design of a preprototype subsystem indicated that by using hollow-fiber technology, the weight and size of the subsystem will be less than for systems based on conventional technologies. Indeed, using worst-case estimates, the membrane-based subsystem will weigh less than half that of subsystems based on conventional technology and have one third the volume.

Based on the results of this highly successful program, we recommend that a preprototype membrane-based dehumidification subsystem be constructed and tested under conditions expected to be present in the EMU. Long-term (90-day) tests should be conducted to verify the reliability of this technology. This follow-on program should also include about 6 months of development work aimed at further reducing the volume of the hollow-fiber module and improving membrane performance. This additional work will result in the optimal membrane-based subsystem for controlling humidity in the EMU.

Additionally, because of the breakthrough in hollow-fiber technology, membrane dehumidification systems should be reconsidered for use in the space station or on long-duration space flights. Using the data obtained in this program, we estimate that a membrane-based subsystem designed for use in the space station will require only about 16 m^2 (175 ft^2) of membrane area--less than half the amount required based on previous work at BRI. The volume of a module for cabin dehumidification would be about 0.085 m^3 (3 ft^3). Thus, the size, weight, and energy requirements of a dehumidification subsystem based on hollow-fiber technology promises to be substantially less than that of a system based on previous membrane technology.

The results of this highly successful feasibility study suggest that the construction and testing of a membrane-based dehumidification demonstration unit would be an appropriate investment of NASA funding. Furthermore, the breakthrough in hollow-fiber technology makes the use of a membrane-based subsystem for dehumidification of spacecraft cabin air extremely attractive. Thus, NASA should consider funding research to reexamine the use of membranes for this application. Additionally, the membrane-based dehumidification subsystem can be combined with the CO_2-removal subsystem, resulting in a small, energy-efficient system to control and revitalize spacecraft atmospheres.

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